Enhanced Bank of Kalman Filters Developed and Demonstrated for In-Flight Aircraft Engine Sensor Fault Diagnostics
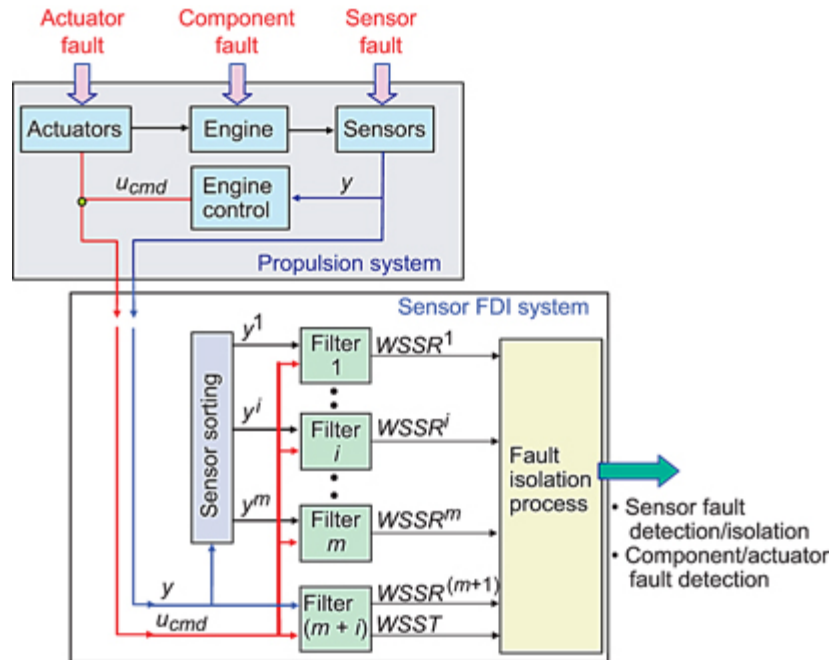
In-flight sensor fault detection and isolation (FDI) is critical to maintaining reliable engine operation during flight. The aircraft engine control system, which computes control commands on the basis of sensor measurements, operates the propulsion systems at the demanded conditions. Any undetected sensor faults, therefore, may cause the control system to drive the engine into an undesirable operating condition. It is critical to detect and isolate failed sensors as soon as possible so that such scenarios can be avoided. A challenging issue in developing reliable sensor FDI systems is to make them robust to changes in engine operating characteristics due to degradation with usage and other faults that can occur during flight. A sensor FDI system that cannot appropriately account for such scenarios may result in false alarms, missed detections, or misclassifications when such faults do occur.

To address this issue, an enhanced bank of Kalman filters was developed, and its performance and robustness were demonstrated in a simulation environment. The bank of filters is composed of $m + 1$ Kalman filters, where m is the number of sensors being used by the control system and, thus, in need of monitoring. Each Kalman filter is designed on the basis of a unique fault hypothesis so that it will be able to maintain its performance if a particular fault scenario, hypothesized by that particular filter, takes place.

Each of the m Kalman filters is designed to estimate the engine state variables and a specific set of sensor measurements using $m - 1$ sensors. The sensor that is not used by a particular filter is the one being monitored by that filter for sensor fault detection. One additional Kalman filter, the $(m + 1)^{st}$, is designed to detect component and actuator faults. This additional filter distinguishes component and actuator faults from sensor faults; therefore, it makes the sensor FDI system robust to component and actuator failure.

Architecture of the sensor fault detection and isolation (FDI) system, where u_{cmd}, control commands; y, sensor measurements; y^i, subset of sensor measurements used by filter i; WSSR (weighted sum of squared residuals), fault indicator signal; $WSSR^i$, fault indicator signal generated by filter i; WSST, fault indicator signal (weighted sum of squared tuners).

Long description of figure Diagram showing the aircraft propulsion system and associated sensor fault detection and isolation (FDI) system. The propulsion system consists of the engine, sensors, actuators, and engine control. The sensors measure the engine output and provide measured values to the engine control. The engine control processes the sensor measurements and sends control commands to the actuators, which set the engine operating condition. The diagram shows that the engine components, actuators, and sensors may encounter faults during flight. These faults can negatively influence the engine control and result in degraded performance of the propulsion system.

Also shown in the diagram is the sensor FDI system. Sensor measurements and control commands from the propulsion system are input to the FDI system. The sensor FDI system first performs sensor sorting to obtain a unique set of sensor measurements for each Kalman filter. A unique set is composed of all sensor measurements except the one that the associated Kalman filter hypothesizes to be faulty. After sensor sorting, the sets of sensor measurements and actuator commands are processed by the bank of Kalman filters. The bank of Kalman filters generates fault indicator signals, which are then provided as input to the fault isolation process. The fault isolation process interprets the fault indicator signals to perform sensor fault detection and isolation, as well as component and actuator fault detection.

With this FDI architecture, where a bank of Kalman filters are running in parallel, each Kalman filter generates a fault indicator signal that indicates the existence of faults in the system being monitored. When a sensor, component, or actuator fails, all the Kalman filters generate large fault indicator signals except for the one that is using the correct hypothesis. Consequently, sensor faults can be detected and isolated, and component and actuator faults can be detected.

This approach was applied to a nonlinear commercial aircraft engine simulation. Its performance was evaluated at multiple power settings during cruise operation with respect to (1) missed detections, (2) false alarms, (3) misclassifications, and (4) robust sensor fault isolation. Among these categories, the most significant result was observed for misclassifications, which are considered to be the worst erroneous diagnosis that the FDI system can generate during flight. At three different power settings, the sensor FDI system was tested with 1000 different events of component or actuator faults in the simulation environment. The sensor FDI system did not classify any of these component or actuator faults as a sensor fault, thus avoiding any misclassifications. Through extensive evaluation, the enhanced bank of Kalman filters technique demonstrated good performance and robustness, indicating that this technology is promising for improving the safety of aircraft gas turbine engines.

Bibliography

Kobayashi, Takahisa; and Simon, Donald L.: Evaluation of an Enhanced Bank of Kalman Filters for In-Flight Aircraft Engine Sensor Fault Diagnostics. ASME Paper GT2004–53640 (NASA/TM--2004–213203, ARL–TR–3252). http://gltrs.grc.nasa.gov/cgi-bin/GLTRS/browse.pl?2004/TM-2004-213203.html

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